

High-Power Single-Frequency Pulsed Laser Based on a Yb-Doped Large-Pitch Photonic Crystal Fiber

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(Received 16 March 2017, in final form 25 April 2017)

We have developed a high-power single-frequency pulsed fiber laser system utilizing a Yb-doped rod-type large-pitch photonic crystal fiber. The maximal peak power is 33 kW with a 0.4-mJ pulse energy and a 70-MHz linewidth, and the average power is 60 W at a 150-kHz repetition rate. At a higher repetition rate, the average power can be increased to 190 W, which is limited by the onset of transverse-mode instability in the large-pitch photonic crystal fiber. The output beam is linearly polarized and shows a good beam quality with a M^2 value of 1.2.

PACS numbers: 42.55.Wd, 42.60.Da

Keywords: Fiber laser, Single-frequency laser, Pulsed laser

DOI: 10.3938/jkps.70.973

I. INTRODUCTION

Fiber lasers fabricated with rare-earth doping elements, such as ytterbium (Yb), erbium (Er), and thulium (Tm), have advanced very rapidly in the last decade and have been successful in generating very high laser powers at the kW level with a good beam quality [1]. Furthermore, the robustness and the ease-of-use of fiber lasers make them very attractive and useful in many scientific and industrial applications. Fiber lasers, however, have some intrinsic limits in generating high-peak-power laser pulses because the limited core size and the long interaction length of the fibers yields many undesired nonlinear effects and damages the fibers at a relatively low laser peak power.

Although fiber lasers are not suitable for the generation of high-peak-power laser pulses, in some spectroscopic applications, fiber lasers are still preferred over bulk-type lasers because rare-earth-doped fiber lasers with broad gain profiles can provide suitable wavelengths that are not possible with bulk-type lasers, which is a very important property for many spectroscopic applications. For the study of laser-based isotope production, in particular, a high-average laser power of more than 100 W, as well as 10's of kW of peak power, is desired with a 1- to 2-GHz or transform-limited linewidth, and the specific laser wavelengths that bulk-type lasers cannot generate are required. Therefore, some novel lasers need to be developed for the simultaneous achievement of high-peak power, high-average power, narrow linewidth, and wavelength tunability.

Some studies have been done on the generation of high-peak-power laser pulses with conventional step-index large-mode-area fibers for spectroscopic purposes. For the light detection and ranging (LIDAR) application, high-peak-power laser pulses with a narrow linewidth have been generated from Er/Yb- or Tm-doped fiber lasers; 0.38-mJ, 3-ns laser pulses were generated from an Er/Yb-doped fiber laser [2], and 0.5-mJ 15-ns laser pulses from a Tm-doped fiber laser [3]. In those reports, however, the linewidth was not measured clearly, and the average power was just 3 - 4 W. For remote sensing of the ocean temperature profile based on Brillouin scattering, 0.5-mJ 10-ns laser pulses with a ~ 70 -MHz linewidth were demonstrated from a Yb-doped fiber laser [4]. However, its beam quality and degree of polarization were not good enough for efficient second-harmonic generation, and the average power was just ~ 0.5 W.

For the generation of high-peak-power laser pulses with a narrow linewidth from fiber lasers, a rod-type photonic crystal fiber (PCF) can be a good candidate because it has a very large core size of 50 - 100 μm and a relatively short fiber length, which is suitable for the suppression of nonlinear effects through the fibers. Rod-type PCFs have been successful for the generation of MW peak-power laser pulses [5], and a high-average-power of 100's of W has been demonstrated [6-9]. However, an early version of the rod-type PCF was not so successful in generating a good beam quality and a high degree of polarization, especially when it was operated at a high-average laser power of more than 100 W.

For the realization of a good beam quality in rod-type PCFs, some novel designs of PCFs, such as distributed-mode-filtering photonic crystal fibers (DMFs) and large-pitch photonic crystal fibers (LPFs), have been devised.

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DMFs utilize high-index ring-shaped elements in their cladding for the suppression of higher-order modes and have demonstrated 110 W of laser output power with a good beam quality ($M^2 \sim 1.1$) and a mJ level of Q-switched pulse energy [10]. However, due to their photonic-band-gap wave-guiding property, DMFs can guide only in a certain wavelength range around 1030 - 1050 nm, which is not suitable for wide wavelength tunability. LPFs utilize a unique hole structure with an optimized hole size and hole-to-hole pitch, which enables a highly preferential guide only for a fundamental mode, and nearly 300 W of laser output power with a good beam quality ($M^2 \sim 1.4$) was demonstrated with an LPF with a 62- μm fundamental-mode field diameter [11]. Moreover, LPFs can support wide wavelength tuning because they do not utilize any resonant mode filtering techniques.

In this paper, we report on the development of a high-power single-frequency pulsed laser based on an LPF. Because of the large core size and the robust single-mode property of a large-pitch PCF, a high peak power of 33 kW and a high average power of 60 W could be achieved simultaneously at a 150-kHz repetition rate. At a higher repetition rate, the average power could be increased to 190 W with a good beam quality.

II. EXPERIMENTAL SETUP

For our laser-based production of calcium and oxygen isotopes, we needed a narrow-linewidth high-power pulsed laser with a wavelength near 1056 nm, which is not easily accessible with bulk-type laser materials. Therefore, we developed a laser system based on Yb-doped fiber lasers which have broad gain profiles around 1030 - 1100 nm. Our laser system has the configuration of a master-oscillator fiber-amplifier composed of a very narrow-linewidth master oscillator and a series of Yb-doped fiber amplifiers, including an LPF-based power amplifier.

As a master oscillator, we used a continuous-wave (CW) distributed-feed-back (DFB) laser diode (LD) with a 20-mW laser power and a few MHz linewidth. The wavelength of the DFB laser was set to 1056 nm by control of the DFB LD's temperature. The DFB LD's laser output was pre-amplified to several watts of pulsed lasers in three fiber amplifiers, as shown in Fig. 1. The first fiber amplifier was for the CW amplification of the DFB LD's laser output and was based on a polarization-maintaining (PM) Yb-doped double-clad (DC) single-mode (SM) fiber with a core size of 6 μm and a cladding size of 125 μm , which was pumped by a 976-nm pump LD. The amplified CW laser power was about 300 mW. The laser beam from the first amplifier was temporally shaped by using an acousto-optic modulator (AOM) with a 13-ns temporal window and a 150-kHz repetition rate, and the average power of the pulse train was 0.3 mW.

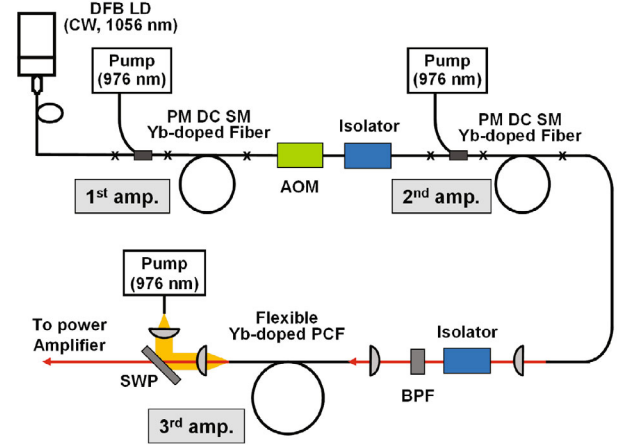


Fig. 1. (Color online) Configuration of the pre-amplifying stage in our laser system. DFB LD, distributed feed-back laser diode; AOM, acousto-optic modulator; BPF, band pass filter.

After the AOM, the laser linewidth increased to ~ 60 MHz. Compared to electro-optic amplitude modulators (EOMs), AOMs are advantageous in generating laser pulses from CW lasers due to their high extinction ratio of more than 50 dB and ease of use, which does not require any bias control (which is necessary for EOMs).

The laser pulses after the AOM were further amplified to ~ 6 W by using two more Yb-doped fiber amplifiers. The second fiber amplifier was the same type as the first one used in the CW amplification of the master oscillator, and the average amplified laser power from the second amplifier was 300 mW. The third fiber amplifier was based on a flexible PM DC SM PCF (NKT photonics) with a mode field diameter of 30 μm and a cladding size of 200 μm . The laser beam from the second amplifier was coupled out to free space and injected into the flexible PCF through two coupling lenses. The 976-nm pump laser beam was also coupled into the flexible PCF through free-space coupling lenses in a direction opposite to that of the signal propagation. Thanks to the large core size and the short length (2.5 m) of the flexible PCF, we could obtain more than 6 W of amplified laser power. On the contrary, when we used a 25- μm core size step-index fiber at the third amplifier, the amplified laser power was limited to ~ 3 W because of the onset of stimulated Brillouin scattering (SBS) [12].

In our final power amplifier, we used an LPF with a hole-to-hole distance of 35 μm and a relative hole size of 0.14. The length of the LPF was 1.2 m, and both ends of the LPF were end-capped for high-peak-power laser operation. The mode field diameter and the first cladding (pump core) diameter of the LPF were 55 μm and 200 μm , respectively. The first cladding was surrounded by the air-gap second cladding, which enabled a high pump-core NA of ~ 0.6 . The air-gap cladding was surrounded by a fused silica glass body with a 1.0-mm outer diameter for the prevention of undesired bending of the LPF. The

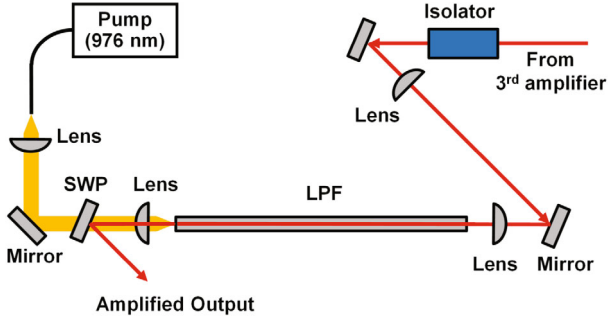


Fig. 2. (Color online) Configuration of the final amplifier based on the LPF. LPF, large-pitch photonic crystal fiber; SWP, short-wave pass mirror.

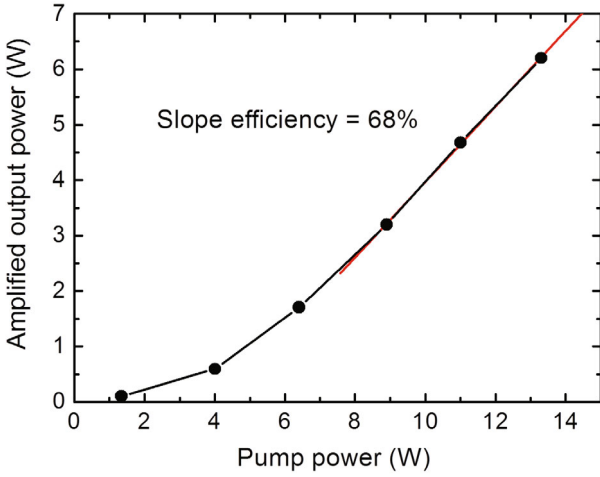


Fig. 3. (Color online) Amplified output laser power of the third amplifier based on the flexible PCF as a function of the pump power.

small-signal pump absorption of the LPF was 24 dB/m at 976 nm. For stable mounting and cooling of the LPF, we installed the LPF on a long aluminum block with a V-groove cooled by circulating water.

The signal laser beam from the third amplifier was injected into the core of the LPF through two coupling lenses, and the pump laser beam was coupled into the pump core of the LPF in the opposite direction, as shown in Fig. 2. For pumping the LPF, we used seven 976-nm 50-W LDs with output fibers with a 105- μm core size and a 0.22 NA. The seven pump lasers were combined into an output fiber with a 300- μm core size and a 0.22 NA, yielding a maximal pump power of more than 300 W. To inject the pump laser beam emitted from the 300- μm core fiber into the 200- μm cladding of the LPF, we used two lenses with different focal lengths, and the pump beam was injected through a short-wave pass mirror, which was used to separate the amplified signal laser from the pump beam path.

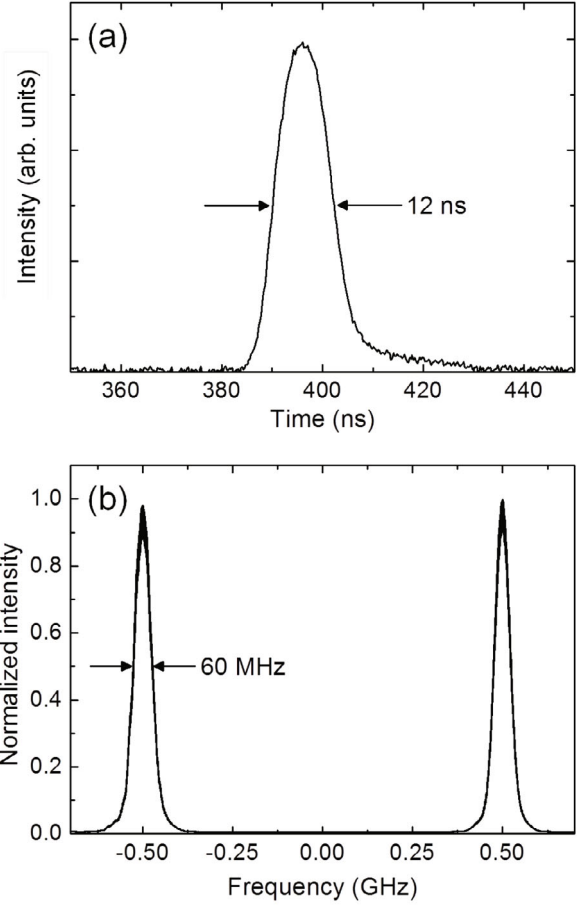


Fig. 4. (a) Temporal pulse shape and (b) spectra linewidth of the third amplifier.

III. RESULTS

Figure 3 shows the amplified laser power from the third amplifier based on the flexible PCF with respect to the pump power. The maximal output power was more than 6 W at a 150-kHz repetition rate, and the slope efficiency was 68%. The pulse duration of the amplified laser pulses measured with a fast photodiode and an oscilloscope was 12 ns, as shown in Fig. 4(a).

To ensure the generation of very narrow linewidth laser pulses before the injection to the final power amplifier, we measured the laser linewidth after the third amplifier by using a scanning Fabry-Perot spectrometer with a 1-GHz free spectral range and a finesse of 150. As shown in Fig. 4(b), the measured linewidth was 60 MHz. We calculated the Fourier-transform-limited linewidth from the measured pulse duration (12 ns), assuming that the temporal pulse shape was Gaussian or super-Gaussian. The calculated linewidths were 37 MHz and 57 MHz for Gaussian and second-order super-Gaussian pulse shapes, respectively, which indicated that our laser pulse shape was more like a super-Gaussian one.

Because of the very narrow linewidth of less than 100

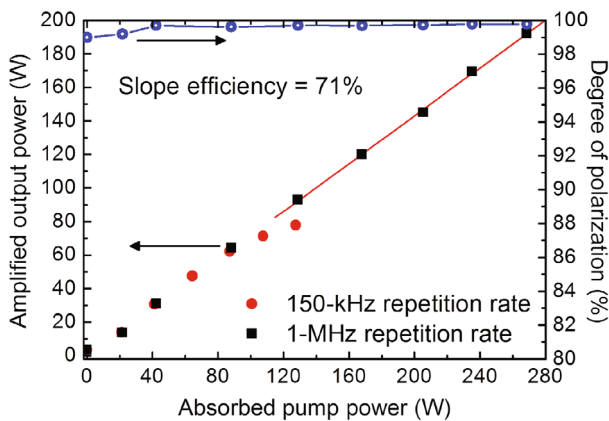


Fig. 5. (Color online) Amplified output laser powers of the final amplifier based on the LPF at the two different repetition rates as functions of the absorbed pump power. The degree of linear polarization at the 1-MHz repetition rate is also displayed.

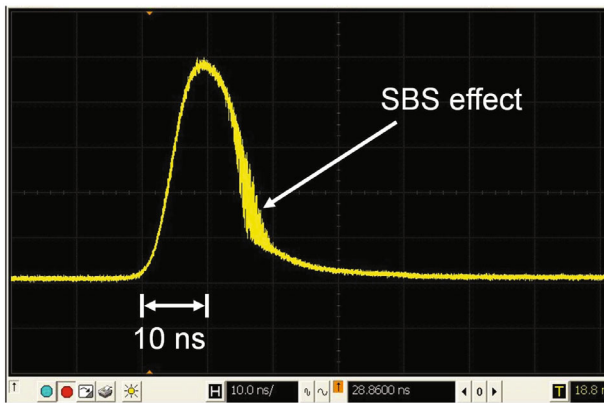


Fig. 6. (Color online) Temporal pulse distortion of the amplified laser pulses in the final amplifier, which is caused by SBS.

MHz and the high peak power of more than several kW in our fiber laser system, SBS is the main limiting factor in increasing the laser pulse energy. Therefore, we operated our laser system in two modes; in the first mode, we tried to maximize the pulse energy at a low repetition rate of 150 kHz, and, in the second mode, the average power was maximized at a high repetition rate of 1 MHz. Figure 5 shows the amplified laser power from the final power amplifier based on the LPF at the two different repetition rates. At a 150-kHz repetition rate, the maximal amplified laser power was limited by the onset of SBS, and one can see a slight roll over of the amplified power around 60 W in Fig. 5. This means that the peak power of the SBS threshold in our final amplifier is 33 kW at a 12-ns pulse duration. At a higher amplified power of 75 W, we observed that the temporal pulse shape was distorted, as shown in Fig. 6, due to the irregular reflection by the acoustic grating generated by SBS.

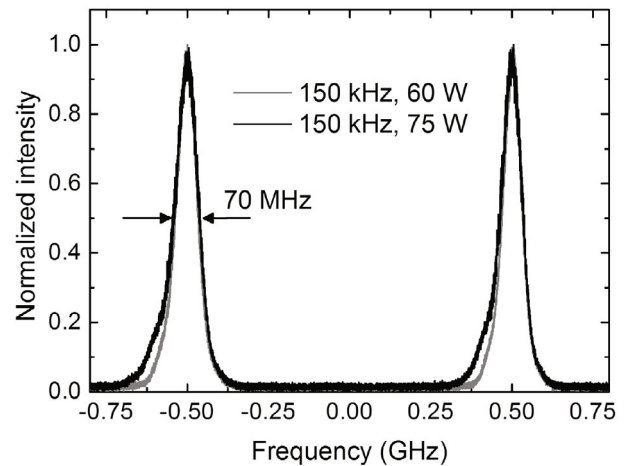


Fig. 7. Linewidth of the laser pulses from the final amplifier at a 150-kHz repetition rate. The amplified powers were 60 W and 75 W.

The linewidths of the laser pulses from the final amplifier were measured with a scanning Fabry-Perot spectrometer, and the results are shown in Fig. 7. At an amplified power of 60 W at 150 kHz, the linewidth was 70 MHz and had a symmetric spectral shape. The slight increase in the linewidth after the final amplifier may be due to the self-phase modulation or to a change in the temporal pulse shape due to gain saturation. At an amplified power of 75 W, which is slightly higher than the SBS threshold, the linewidth was almost the same, but the spectral shape became asymmetric. Although such a spectral change after the final amplifier needs further study based on numerical simulations of laser pulse propagation through optical fibers, we verified experimentally that powerful single-frequency laser pulses with a 0.4-mJ pulse energy and a 33-kW peak power could be generated in our LPF-based amplifier.

When our laser system was operated at a high repetition rate of 1 MHz, we could increase the amplified output power up to 190 W without any sign of SBS, as shown in Fig. 5. The slope efficiency was 71% with respect to the absorbed pump power. At the maximal power of 190 W, the laser pulse energy was 0.19 mJ, and the laser peak power was 16 kW with a 12-ns pulse duration, which is much lower than the SBS threshold of our final amplifier (33 kW). The degree of polarization of the amplified laser beam was also measured with a polarizer; the laser beam was transmitted through an external polarizer, and the maximal and the minimal powers ($P_{\max}$ and $P_{\min}$) of the transmitted laser were measured as the axis of the external polarizer was rotated. After the measurements of $P_{\max}$ and $P_{\min}$, the degree of polarization was calculated as $(P_{\max} - P_{\min}) / (P_{\max} + P_{\min})$. It is noticeable in Fig. 5 that the high degree of linear polarization of more than 99% was maintained through the LPF-based amplifier even though our LPF did not have any polarization-maintaining structure like stress-

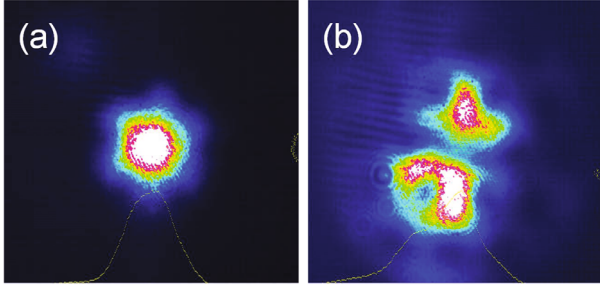


Fig. 8. (Color online) Beam mode patterns of the final amplifier at a 1-MHz repetition rate (a) before and (b) after the onset of TMI.

applying parts. This is because the LPF is kept very straight on the mount without any serious stress on the LPF.

Despite the laser peak power being much lower than SBS threshold at a 1-MHz repetition rate, we could not increase the amplified power higher than 190 W because transverse-mode instability (TMI) was observed at powers above 190 W, as shown in Fig. 8. TMI is a phenomenon in which the transverse mode of a fiber laser suddenly becomes unstable and fluctuates between fundamental and higher-order modes when an output power reaches a certain threshold [13]. TMI has been observed in many high-average-power lasers based on large-mode-area gain fibers, including photonic crystal fibers and conventional step-index fibers. The origin of TMI is known to be thermally-induced long-period gratings generated by the thermo-optic effect and the interference between the fundamental and the higher-order transverse modes in gain fibers [14]. In particular, rod-type gain fibers, such as our LPF, which have a large core size and a high thermal load in a short length of the fiber, show a relatively low threshold of TMI.

Figure 9 shows the beam-mode patterns of the final amplifier at various output powers. The beam changes gradually from a star-like shape to a circular one as the output power increases, and the beam size also decrease slightly at a high output power. Such beam-mode shrinking has been reported to be caused by a thermally-induced waveguide change in very large-mode-area gain fibers, such as LPFs [15]. The beam quality (M^2 value) of the amplified laser beam was measured to be 1.2 - 1.3 at output powers of more than 60 W.

IV. CONCLUSION

A high-power single-frequency pulsed fiber laser based on a Yb-doped rod-type LPF has been developed for spectroscopic applications in laser-based isotope production, which requires a high-power pulsed laser with a very narrow linewidth. The power amplifier based on the LPF, which has a large mode field diameter of 55 μm and a short fiber length of 1.2 m, was successful in generating

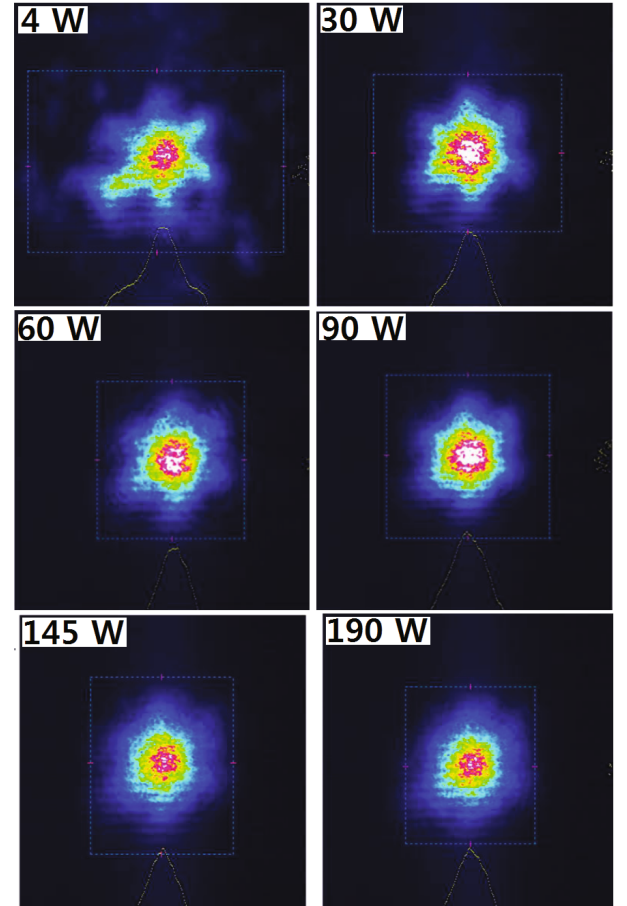


Fig. 9. (Color online) Evolution of the beam mode pattern of the final amplifier as the amplified power is increased at a 1-MHz repetition rate.

33-kW peak-power laser pulses with a narrow linewidth of 70 MHz. The pulse energy and the pulse duration were 0.4 mJ and 12 ns, respectively, yielding a 60-W average power at a 150-kHz repetition rate. At a higher peak power, the temporal and the spectral shapes of the laser pulses were distorted by SBS. When we operated the laser system at a high repetition rate of 1 MHz to lower the laser's peak power well below the SBS threshold, the maximal average output power of the LPF-based power amplifier was 190 W, which was limited by the onset of TMI. Below the TMI threshold of 190 W, the beam quality (M^2) was 1.2 - 1.3, and a high degree of linear polarization was achieved.

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